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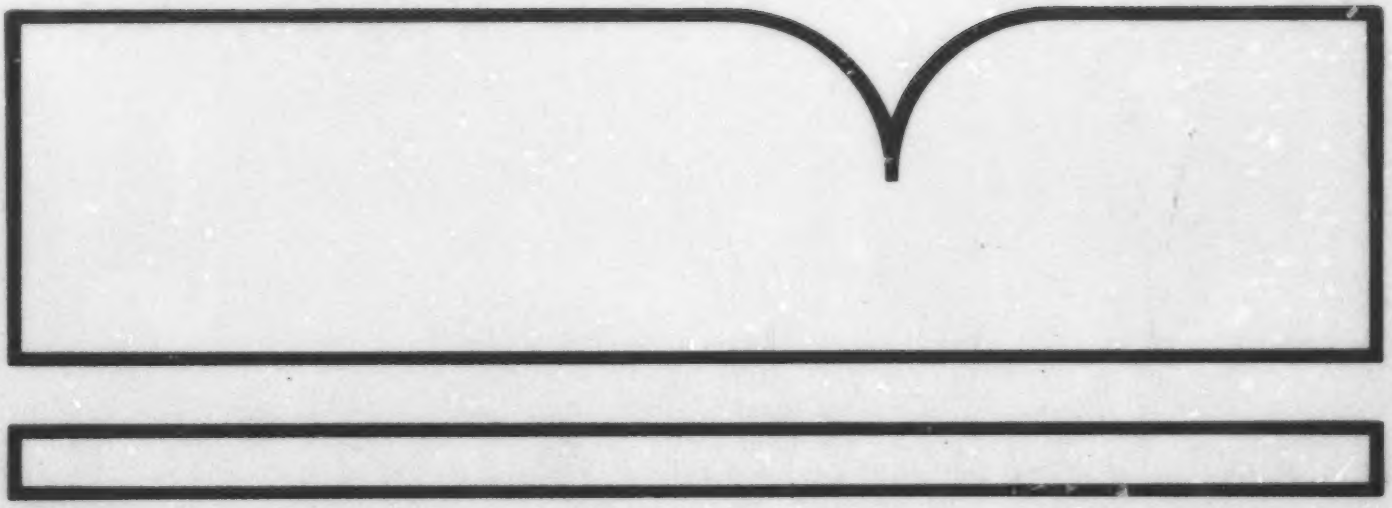

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16. ABSTRACT

Studies were conducted which examined the effects of radio frequency (RF) radiation on heart rate (HR), deep body temperature (TEMP), and electrocardiographic (ECG) waveform parameters in anesthetized rats. One group of animals was exposed to two power levels of continuous wave RF radiation averaging 1.0 and 7.4 W/kg at a frequency of 600 MHz. A second group of animals, treated identically but not exposed to RF radiation, served as a control. The electrodes used to monitor the ECG during RF exposure were fabricated using carbon-loaded Teflon wire, a semi-conductor material that does not perturb the RF field. Analyses of the ECG were conducted using a recently developed computer-assisted procedure which quantitates HR and waveform intervals over 25-40 individual ECG complexes. There were no artifacts or arrhythmias in the ECGs of the animals exposed to RF radiation. There was a significant linear correlation between HR and TEMP in the RF-exposed group which was not present in the control group.

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Improved technique for monitoring electrocardiograms during exposure to radio-frequency radiation

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WATKINSON, WILLIAM, P., AND CHRISTOPHER J. GORDON. *Improved technique for monitoring electrocardiograms during exposure to radio-frequency radiation.* Am. J. Physiol. 250 (Heart Circ. Physiol. 19): H320–H324, 1986.—Studies were conducted utilizing improved methodology that examined the effects of radio-frequency (RF) radiation on heart rate (HR), deep body temperature (T_{co}), and electrocardiographic (ECG) waveform parameters in anesthetized rats. One group of animals was exposed to two power levels of continuous-wave RF radiation averaging 1.0 and 7.4 W/kg at a frequency of 600 MHz. A second group of animals, treated identically but not exposed to RF radiation, served as a control. The electrodes used for monitoring the ECG during RF exposure were fabricated from carbon-loaded Teflon wire, a semiconductor material that does not perturb the RF field. Analyses of the ECG were conducted by use of a recently developed computer-assisted procedure that quantitates HR and waveform intervals over 25–40 individual ECG complexes. There were no artifacts or arrhythmias in the ECGs of the animals exposed to RF radiation. There was a significant linear correlation between HR and T_{co} in the RF-exposed group that was not present in the control group.

rat; heart rate; temperature; carbon-loaded Teflon electrodes

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THE EFFECTS OF EXPOSURE to radio-frequency (RF) electromagnetic radiation on the cardiovascular system remain controversial. Investigations in this area, in addition to being limited in number, have often yielded contradictory results. For instance, heart rate (HR) has been reported by various authors to increase (2, 6, 9), decrease (11, 12, 18), or remain unchanged (3, 10, 19). Furthermore, one group (13, 14) has reported opposite effects following dorsal (tachycardia) and ventral (bradycardia) exposure to RF radiation in the same experimental preparation. The influence of RF radiation on other basic indexes of cardiovascular function, such as the electrocardiogram (ECG) and systemic blood pressure, are largely unknown.

The paucity of reliable information may be attributed to several factors. First, the diverse nature of RF radiation itself introduces numerous complexities and permutations involving such parameters as frequency, modulation, and pulsed- versus continuous-wave exposure. Furthermore, the effects are often dependent on the rate of absorbed energy, which in turn is a function of the orientation of the animal as well as the frequency and power density of the incident RF radiation field. In addition, such factors as the type of exposure apparatus (waveguide vs. anechoic chamber), the type of experimental preparation (in situ vs. isolated heart), and the weight and physical characteristics of the animal model (homeotherm vs. poikilotherm) greatly influence power absorption. There has been little commonality with respect to these experimental variables in the studies reported to date. Second, there are important methodological limitations that must be observed when studying the effects of RF radiation exposure on the cardiovascular system. Primarily, these concern the induction of measurement artifacts when metal and/or KCl-filled glass electrodes are positioned within the exposure field (19). The prohibition of metallic or glass electrodes discourages the use of traditional means of monitoring cardiovascular parameters using wires, needles, transducers, etc. Finally, although it is well known that RF radiation induces heating of body tissues, there has often been a failure to control or account for this effect in past studies investigating cardiovascular effects. Thus it has not been established whether exposure to RF radiation affects HR per se or whether HR changes secondarily in response to a concomitant increase in body temperature.

The recent increase in clinical usage (1, 16, 17) of RF radiation therapy (e.g., cancer treatment, bone healing), as well as the many present and potential commercial applications (e.g., communications systems, home appliances, video monitors), emphasize the need for new methodologies to accurately assess the physiological effects of RF exposure on the intact animal. This paper will report the results of a recent study that employed an improved technique to monitor and analyze the ECG during RF exposure. To test this methodology, rats were exposed to two power levels of RF radiation at a frequency of 600 MHz while the ECG, HR, and deep body

temperature (T_{co}) were continuously monitored. The electrodes used for monitoring the ECG were fabricated from carbon-loaded Teflon wire, a semiconductor material that does not perturb the RF field.

METHODS

Experimental procedure. Naive, male Sprague-Dawley rats (123–124 days old) were used in this study. Animals were obtained from Charles River breeding laboratory (Kingston, NY) and were housed in plastic cages on pine shaving bedding in a temperature- (22–26°C) and light-controlled (light:dark 12:12) biologically clean room until studied. They were allowed access to tap water and laboratory chow ad libitum. The weight range for these animals was 426–554 g.

For this study, special electrodes were constructed using commercially available high-impedance semiconducting line (0.030 in. diam, carbon-loaded, nylon-coated Teflon wire; Polymer Corp., Reading, PA). This wire was developed specifically for applications involving RF radiation above 500 MHz and has been shown not to alter the electromagnetic field or to influence radiant energy deposition at these frequencies (7). Approximately 60 cm of this high-impedance wire was joined to 10 cm of conventional wire (30 gauge, plastic-coated copper) using a wire wrapping technique. The proximal end of the copper wire was fitted with a terminal connector (TIP plug) compatible with the recording system. Approximately 2 cm of the nylon coating was stripped from the distal end of the high-impedance wire. Tests conducted with a square-wave generator indicated there was no noticeable attenuation of the magnitude or response time of electrical signals using this electrode.

Rats were anesthetized with pentobarbital sodium (50 mg/kg ip) and instrumented with four electrodes. The exposed end of the high-impedance wire was implanted subcutaneously on the ventral surface at the juncture of the extremities and secured with tape. Animals were placed in the exposure apparatus in a prone position and lightly restrained with tape. All electrodes were brought behind the animal's back, twisted together, and tunneled through a small opening in the waveguide. Rectal temperature was monitored using a temperature probe that is not perturbed by RF radiation (Vitek, Boulder, CO; model 101). The probe was inserted 6 cm past the anal sphincter. All wires were shielded from the point of exit from the exposure apparatus to the chart recorder to minimize electrical noise.

Exposure apparatus. The exposure apparatus was constructed using a straight section of WR-1500 waveguide 60 cm in length with coaxial cable adapters connected to each end. Temperature of the waveguide was controlled by immersing it in a water bath thermostabilized to 30°C. Room air was continually circulated through the waveguide. The incident power from an MCL RF generator (La Grange, IL; model 15222) was initially passed through a bidirectional coupler (Narda, Hauppauge, NY; model 3020A) that provided ports for the monitoring of incident power entering the waveguide and reflected power emanating from the waveguide to the RF generator. Another bidirectional coupler was placed at the opposite end of the waveguide and served to monitor transmitted power. Power was measured with Hewlett-Packard power meters (Palo Alto, CA; model 436A). The power absorbed by the rat was calculated by the incident minus reflected and transmitted power. Dividing the absorbed power by the rat's body mass gave the specific absorption rate (SAR) in watts per kilogram. The frequency of the continuous-wave RF radiation was 600 MHz.

The experimental procedures and apparatus were tested by subjecting rats to both intermittent-power-on and continuous-power-on exposure regimens to determine the effect of RF radiation on the ECG signal. It should be noted, however, that only continuous power exposure was used for the study procedures described below.

Experimental protocol. Animals were randomly divided into two treatment groups. The first group ($n = 5$) was exposed to two levels of RF radiation while the second group ($n = 5$) served as a control.

The experimental protocol for the RF-exposed group consisted of four consecutive 15-min segments: control, low-power exposure, high-power exposure, and recovery. The average SAR for the low-power segment was 1.0 ± 0.005(SD) W/kg while the SAR for the high-power segment averaged 7.4 ± 0.1 W/kg. HR, ECG, and T_{co} were monitored throughout the experimental procedure. ECG signals were processed and analyzed in the final minute of each 15-min segment using a computer-assisted signal averaging procedure previously described (20).

With the exception of the RF exposure, the control group was treated identically to the treated group, and ECG analyses were conducted at similar times.

Statistics. Statistical analyses were conducted using the general linear models procedures of the Statistical Analysis System (15). The least-square means procedure and the multivariate profile analysis technique were used to test for differences between groups. The simple regression procedure was used to test for correlations between variables within groups. Probability values less than 0.05 were considered significant.

RESULTS

A representative ECG signal obtained during periods of rapid, intermittent exposure to high-power RF radiation is shown in Fig. 1. As can be seen, there were no noticeable artifacts, nor was there attenuation of the signal associated with the RF exposure.

The mean values for T_{co}, HR, and ECG intervals for both treatment groups for the four time periods are listed in Table 1. There was a continuous increase in T_{co} in both groups over the course of the experiment. Overall, the magnitude of this increase was larger (2.54 vs. 1.26°C) in the RF-exposed animals than in the control animals. This final temperature differential may be attributed to the increased energy deposition associated with the high-power RF radiation. With the exception of the time period in which the high-power RF radiation exposure occurred, the incremental increase in T_{co} was nearly uniform throughout the experiment for both groups of animals.

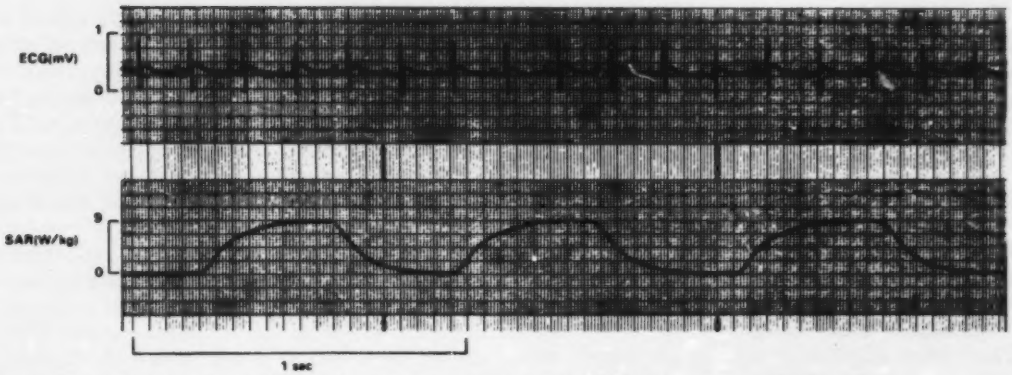

FIG. 1. Representative electrocardiographic waveform of adult male rat obtained during exposure to radio-frequency (RF) radiation. *Chart tracings* show lead II of electrocardiogram (ECG) and specific absorption rate (SAR) of RF radiation. RF exposure was intermittent and manually controlled. Chart speed was 100 mm/s. *Note*: although peak SAR values are reached instantaneously, due to capacitance of the measurement instrumentation, chart tracings exhibit an artifactual lengthy rise and fall time.

TABLE 1. *Temperature, heart rate, and electrocardiographic waveform parameter values for adult rats*

Parameters	Time, min			
	0–15	16–30*	31–45†	46–60
Control, sham exposed				
Temp, °C	36.50±0.16	37.00±0.21	37.08±0.42	37.76±0.23
HR, beats/min	345.88±5.29	358.80±7.95	337.80±11.95	348.95±15.94
P-R interval, ms	43.04±3.46	39.53±3.80	39.13±3.40	41.38±2.96
R-αT interval, ms	32.91±2.56	32.53±2.48	31.01±2.46	30.05±2.08
P-wave duration, ms	13.17±1.82	13.35±1.45	13.64±0.77	15.47±1.31
QRS duration, ms	19.20±1.63	19.03±1.17	18.37±1.10	18.21±1.51
αT-P segment, ms	98.44±4.21	95.40±4.20	108.90±6.24	102.49±7.82
Treated, RF exposed				
Temp, °C	36.28±0.26	36.86±0.30	38.32±0.25	38.82±0.26
HR, beats/min	313.04±10.06	326.55±12.50	353.92±8.80	370.67±12.72
P-R interval, ms	42.30±1.86	41.27±1.99	39.10±1.77	37.65±1.59
R-αT interval, ms	31.24±2.06	29.73±1.91	29.48±2.04	29.20±1.99
P-wave duration, ms	16.30±2.50	15.81±2.52	15.98±2.40	14.25±2.39
QRS duration, ms	18.86±0.47	18.59±0.50	17.54±0.71	17.20±0.61
αT-P segment, ms	118.41±6.78	114.03±8.01	101.80±5.35	94.76±6.49

Values are means ± SEM for 5 animals. Adult rats were exposed to 2 power levels of continuous-wave radio-frequency (RF) radiation averaging 1.0 and 7.4 W/kg at a frequency of 600 MHz. HR, heart rate; ECG, electrocardiogram. Note: definition of ECG intervals, waves, and segments have been modified slightly from traditional clinical usage to accommodate the rat ECG (e.g., adult rats have broad, gradually diminishing T wave and no S-T segment; αT point represents apex of T-wave). For more detailed information see Watkinson et al. (20). * Low-power RF-exposure time; † high-power RF exposure time.

There was an increase in HR in the irradiated group animals in conjunction with the increase in T_{co} (Table 1). The HR response of the control group animals, however, was equivocal and did not follow the T_{co} increase seen in these animals. To minimize individual variability and facilitate between-group comparisons, all values were normalized with respect to their initial control values, and these data are illustrated in Fig. 2. As can be seen, there was a significant linear correlation between the increases in HR and T_{co} in the RF-exposed group that was not present in the control group. The lack of correlation in the control group animals may be attributed to the decrease in HR observed during the third 15-min time period.

There were no arrhythmias observed in the RF-exposed rats at any time during the experimental procedure. Quantitative analysis of the duration of ECG waveform components shows a consistent, though not significant, decrease in the values observed during RF exposure (Table 1). These reduced intervals are an expected consequence of the elevated HR induced by rising T_{co}. The data obtained from the control animals are relatively inconsistent and do not exhibit any trend.

DISCUSSION

The present study clearly demonstrates the feasibility of monitoring functional changes in electrocardiographic parameters during periods of RF exposure. The results of past studies using mammalian animal models in which similar investigations were undertaken have been clouded by the use of metallic apparati within the exposure field. To our knowledge, the present study represents the first utilization of "RF transparent" high-impedance wire for ECG analysis during periods of RF exposure in the intact mammal. The capability of conducting such studies should prove useful in investigating

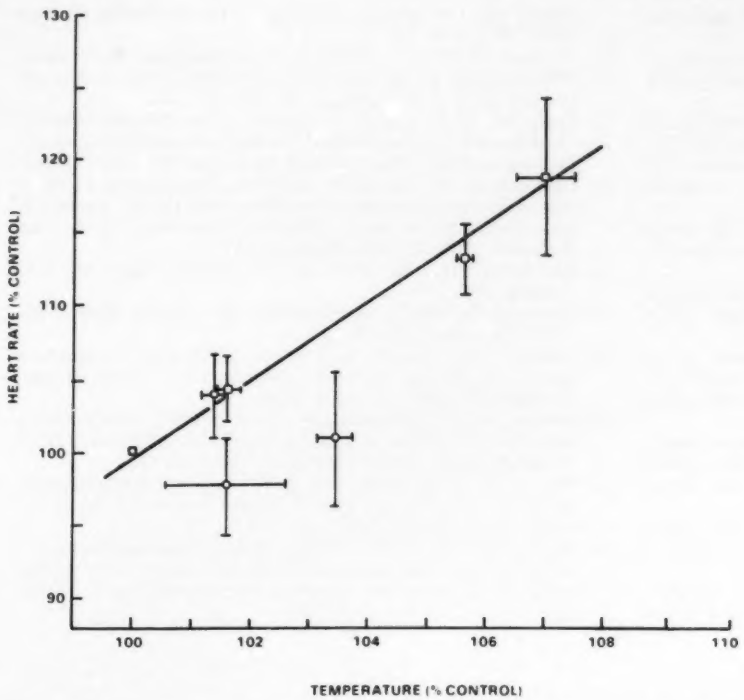

FIG. 2. Correlation between relative heart rate and temperature (means ± SEM) of adult, male rats before, during, and after exposure to 2 power levels of radio-frequency (RF) radiation. Data were first normalized with respect to initial preexposure values. *Circles* (○) indicate data from similarly treated control group ($n = 5$) and *squares* (□) indicate data from RF-exposed group ($n = 5$). Linear regression analyses were conducted and the best-fit linear regression equation was plotted for RF-exposed group values. Correlation coefficient for RF-exposed group values was significant ($P < 0.001$).

the cardiovascular effects of commercial and industrial applications of RF radiation and extrapolating these results to humans.

Although the data presented in this study are primarily illustrative in nature, an interesting finding involved the relationship between T_{co}, HR, and ECG intervals and the differential changes observed following exposure to RF radiation. In the RF-exposed animals, there was an expected increase in T_{co} above control levels in conjunction with the increased energy deposition. There was a concomitant linear increase in HR and a decrease in ECG intervals. The response seen in the control group animals, however, was significantly different. The increase in T_{co} observed in this group was not accompanied by parallel increases in HR or consistent decreases in ECG intervals.

The meaning of these results is unclear; however, they may be related to the specific mode of the T_{co} increase. A frequency of 600 MHz is near resonant for the rat (4, 5). This implies that during exposure there will be a relatively rapid rate of heating deep within the body. This is a considerably different thermal environment compared with that of the control animals, which warmed passively within the waveguide. It is possible that these two different modes of body warming may have accounted for the different relationship of HR versus colonic temperature in the control and experimental groups. It is also recognized that the anesthetic used in the present study may have contributed to the observed effects. Pentobarbital sodium affects both HR and thermoregulatory function (8). Furthermore, the depth of anesthesia may vary inversely with changes in body temperature. Thus it is possible that there may have been a modulation of the effects produced by the differential heat inputs in the presence of the pentobarbital anesthesia. These interesting observations clearly merit further investigation.

In conclusion, this study has demonstrated an improved technique for monitoring electrocardiographic function during exposure to RF radiation. In addition, this study has shown that exposure to near-resonant RF radiation in the pentobarbital-anesthetized rat produces a chronotropic effect in the absence of an arrhythmogenic effect. It will be of future interest to assess the effects of RF radiation on cardiac physiology using these techniques in the unrestrained, unanesthetized animal.

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